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SHAPE MEMORY ALLOY ACTUATORS IN A SIMPLE FORCE-REFLECTING TELEOPERATOR

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A one-degree-of-freedom prototype was constructed to investigate the potential of shape memory alloy (SMA) wires as actuators in force-feedback teleoperated systems. One possible application would be in force-reflecting exoskeletons. A simple on-off system controlled the master and slave actuators of the prototype. The prototype serves as a proof-of-concept model and a foundation for a more sophisticated system with microprocessor-controlled feedback and pulse width modulation (PWM) power sources. Additional experimentation provided data on SMA wire cooling times in air, in a water/glycol mix, and in distilled water. An attempt to use infrared (IR) temperature measurement to improve power control (and thus reduce response time) was not successful.

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PREFACE

This report documents work that began in the summer of 1991, and continued into early 1992. Lt Hasser worked with Prof. Edgar Munday of the University of North Carolina at Charlotte. Prof. Munday was sponsored by the AFOSR Summer Research Program. For completeness, the entire report that Prof. Munday submitted to fulfill his obligation has been included as an appendix. This inclusion created some unavoidable redundancy between the body of this report and its appendix; however, the body of the report retains its coherence, and Prof. Munday's work is represented in the appendix as he originally authored it.

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INTRODUCTION

A material that exhibits the shape memory effect (SME) may be easily deformed when it is cold. Heating the material will return it to the shape it held prior to deformation. In this manner, the material "remembers" its original shape. Investigators have observed the shape-memory effect in certainalloys, called shape memory alloys (SMA), for quite some time [1, 2].

An alloy of nickel and titanium dominates the SMA field. Its common name, Nitinol, is a concatenation of the chemical symbols "Ni" and "Ti" with "NOL," for the U.S. Naval Ordnance Laboratory, where the material was developed during sonar research. Nitinol has well-known properties [3, 4]. For this effort, a form of Nitinol known by the trade name "BioMetal" was used; it is further described in the appendix.

Shape memory alloys can exist in two different crystalline phases [5, 6]. At cooler temperatures, SMA material exists in a martensitic crystalline state. This means that the planes of atoms in the material are arranged accordion-style, like seats in a movie theater (with the movie patron looking between the heads of the people in the next row). This arrangement is called a "twinned structure." External forces can easily deform the alloy, just as a bending force will deform a copper wire.

As the martensite-phase alloy deforms, the planes of atoms slide, in a process referred to as "de-twinning." Heating the alloy will reverse the deformation and cause the alloy to "remember" its original shape. This reversal occurs as the heat forces the atoms into a tightly arranged body-centered cubic

structure, similar to a formation of troops standing at attention. In this phase, the austenite phase, the alloy behaves more like steel than copper, and is not easily deformed.

As the alloy cools from austenite form to martensite form,

the atomic lattice planes shift slightly back to the twinned arrangement, but the overall shape of the alloy does not change. The shape memory effect described here, where external forces must deform the martensite material if it is to change shape during heating, is called the "one-way shape memory effect." A two-way effect, with remembered shapes for both the cool martensite and hot austenite phases, exists but is beyond the scope of this report. The value of the one-way SME may be realized if SMA is formed into wires or springs. SMA wires and springs can perform significant work and function as small actuators.

Generally, small actuators based on conventional technologies will have lower power-to-weight ratios than larger devices. The exceptional power-to-weight ratio of Nitinol puts it in a class by itself when compared to actuators of similar weight [7]. Temperature-induced changes in shape and its unusually high power-to-weight ratio make the alloy useful for many special actuating and fastening applications [6]. The fact that SMA wires can only contract up to about 5% of their length (roughly an order of magnitude less than human muscle) can be a significant design limitation, though larger contractions available from springs may offset this problem somewhat.

Investigators have examined the use of Nitinol wires and springs in small scale robotic systems, but not in teleoperated systems with force feedback [7, 8, 9, 10, 11, 12]. Our objective is to evaluate SMA technology for possible use in force-reflecting hand masters and actuators.

FOUNDATION FOR THE SMA FORCE FEEDBACK APPROACH

Previous work on SMA actuators provides a groundwork for application to force-feedback systems. Investigators have characterized the phase transformation versus strain, the phase transformation versus stress, and the stress versus strain properties of SMA wires [6]. Ikuta has produced a working device using electrical resistance feedback [13]. He describes electrical resistance and temperature as the two internal state variables of SMA materials. Kuribayashi has tested a force controller for SMA actuators [14]. This work shows that SMA actuators can be controlled well for the force-feedback application.

Evaluating the feasibility of an SMA force-feedback mechanism will require a multi-stage effort. First, a model should show that two SMA systems can work together in a stable and useful combination: the master servoed on force and the slave on position. Our initial goal was to develop this model.

Subsequent effort should reveal the most appropriate state variables to use in the control scheme, and develop an electrical power controller compatible with system requirements. Our current research focuses in this area. Later research should continue to address two of the most difficult problems: cooling the SMA actuators and designing them in a way that effectively uses their limited linear contraction distances.

CONSTRUCTION OF AN SMA FORCE-FEEDBACK PROTOTYPE

A proof-of-concept prototype served as our test apparatus. Figure 1 shows the mechanical configuration of the master, and Figure 2 shows the slave:

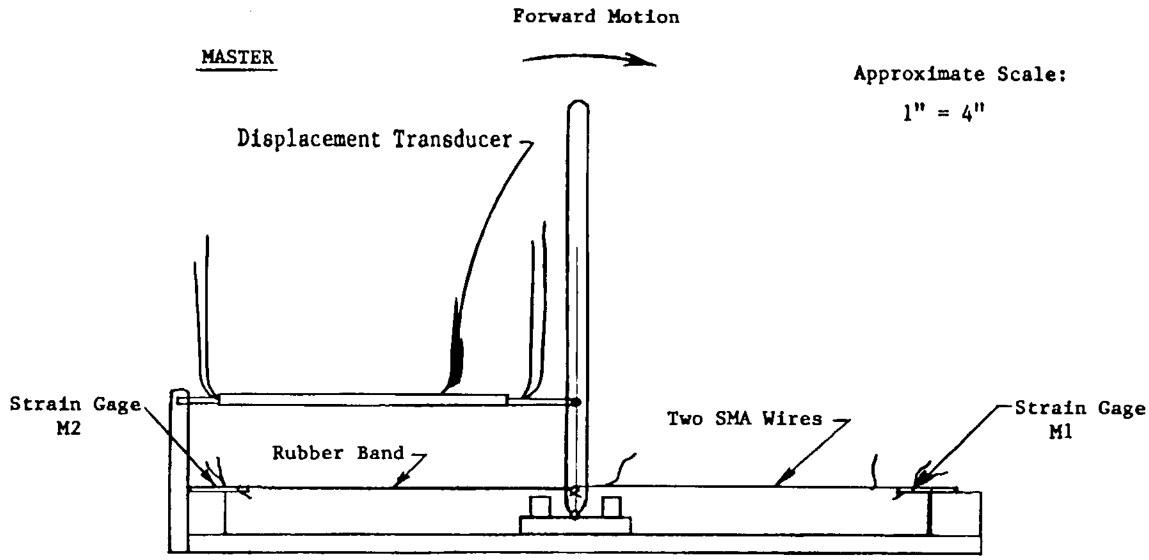

Figure 1. Force-reflecting master.

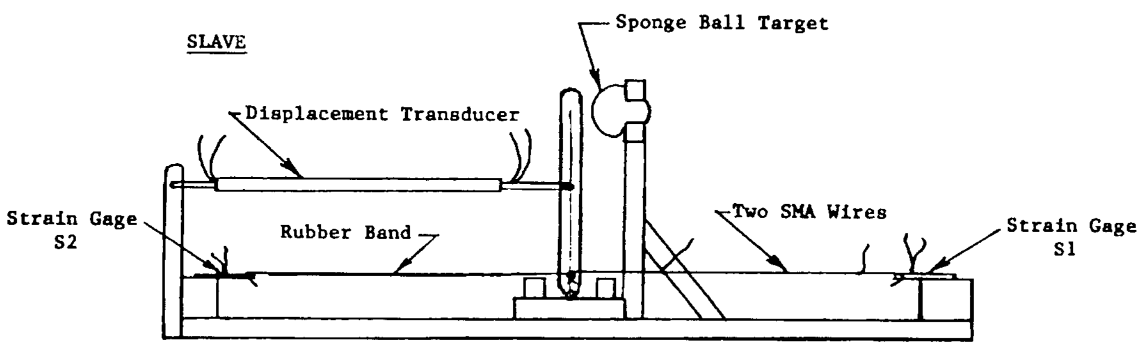

Figure 2. Position-controlled slave and its target.

Both the master and slave levers pivot at the base, with actuator attachments just above the pivot point. Both SMA wire pairs are connected mechanically in parallel, but electrically in series (to reduce the current requirements). The slave actuators pull together against the rubber band to control the position of the slave. The master actuators relax together to allow the master rubber band to provide force feedback and contract to counteract the feedback force.

A Wheatstone bridge composed of four strain gauges provides force sensing to the controller. One strain gauge was connected between mechanical ground and each of the following: master SMA wire, slave SMA wire, master rubber band, and slave rubber band. The initial displacement transducer consisted of an infrared transistor fixed in one end of a tube and an infrared light-emitting diode (LED) on the other end. The LED was displaced back and forth by the motion of the master or slave. These transducers demonstrated the function of the system but did not have satisfactory linearity or resolution. We eventually replaced the initial transducers with Linear Variable Differential Transformers (LVDT's) to improve the quality of the position sensing. The compact LVDT's use a ferrous rod sliding inside cylindrical transformer windings to produce an analog output with theoretically infinite resolution.

CONTROL OF THE SMA FORCE FEEDBACK PROTOTYPE

The initial model uses a simple bang-bang (on-off) control system for both the master and the slave. The bang-bang control works like a very rapid version of a home furnace control, in which the controller turns the system completely on or off, depending on the thermostat setting (desired output) and the temperature reading (input).

The position sensors serve as the sole input to the slave control circuit. Figure 3 shows that the system uses the difference between the master and slave position as the input to the slave actuator control:

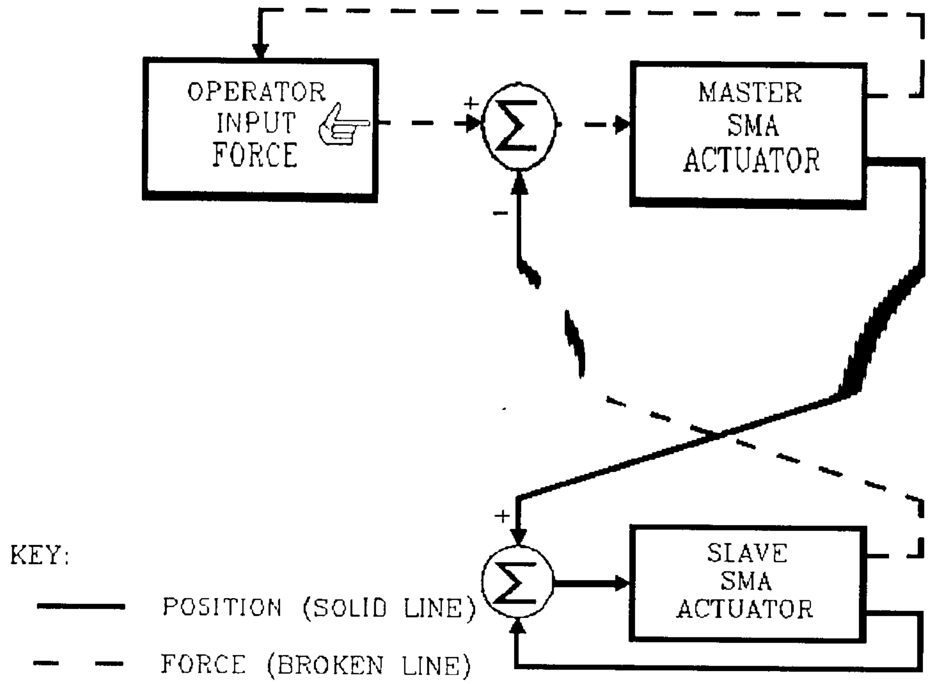

Figure 3. Block Diagram of SMA Control System

The force sensors and the operator's finger serve as the inputs to the master control circuit. Figure 3 also shows how the difference between the force exerted by the operator's finger (upon the master) and that applied against the target (by the slave) serves as the input to the master actuator control. The force controlled by the master actuators (mitigating the rubber band force) is fed back to the operator's finger. Details of the control system, including schematic diagrams, appear in Appendix A of this report.

While position and force information will serve as the main control inputs for a force-reflecting teleoperator, a control system for SMA actuators would ideally take advantage of internal state variables of the SMA material.

The SMA actuators can only perform useful work when their phase transformation is precisely controlled, and they are

maintained within a narrow temperature range. Operation outside of this temperature range is inefficient and slows actuator response; operation above the austenite finish temperature, A_f, also risks damage to the actuators. State variables such as temperature and electrical resistance have direct relationships with the SMA phase transformation, and are useful for optimal control of the actuators.

Experimentation with inexpensive infrared (IR) temperature sensors has not led to a useable method of temperature sensing (see Appendix A). We plan to try an IR sensor matched to the spectra of the heated SMA wire, but getting a significant IR signature from a wire only 150 microns (0.15 mm) thick remains a challenge.

We avoided thermocouple temperature sensing due to the difficulty of attaching the thermocouples to wires as small as 150 microns. It was also thought that the thermal mass of the thermocouple would be non-trivial compared to the tiny actuator wires, introducing measurement delays and error.

Kuribayashi reported success with closed-loop control using a Cu-Constantan thermocouple lashed to a larger, 500 micron (0.5 mm), SMA wire [15]. The thermal mass of the thermocouples was probably not as significant with respect to the 0.5 mm wires as it would be with respect to our thinner (0.15 mm) wires, and attachment of the thermocouples to the larger SMA wires proved achievable in Kuribayashi's tests. Thermocouple temperature sensing may not be feasible with smaller wires; however, Kuribayashi's success encourages further evaluation of the use of thermocouples.

Even if an appropriate temperature sensor was to be developed, temperature sensing would not provide an ideal solution. The hysteresis of the temperature curve would be a disadvantage for control application. The requirement to instrument each actuator with a temperature sensor would introduce added complexity.

Resistance feedback may provide a more practical alternative for sensing the state of the phase transformation. With a current source driving the SMA wires, resistance of each actuator could be calculated from a measurement of the voltage potential across the actuator, without any further instrumentation. Ikuta reported successful use of resistance feedback for accurate position control of SMA actuators [13].

While resistance feedback may be more elegant than temperature feedback, we have not yet shown that resistance feedback is feasible when both position and force vary. Because our investigation of temperature and resistance feedback was just beginning, the initial proof-of-concept model did not take advantage of these two internal state variables.

SYSTEM PERFORMANCE

Initial trials demonstrated good slave response speed in forward motion. After installation of the LVDT's, response delay was barely perceptible. The slave followed the master closely, and the master SMA wires acted quickly to mitigate the force of the master rubber band until the slave contacted the sponge ball. The second prototype will be instrumented for data collection so that quantitative results can be obtained.

Reverse motion of the slave, corresponding to the cooling and relaxation of the slave SMA wire, was noticeably slower.

The master's slow response to contact with the sponge ball target was not as noticeable, since the target was so compliant; however, the master would not have been able to adequately simulate contact with a stiffer surface.

If the master was released suddenly, it would not return immediately to its start point. A delay while the master wires cooled was accompanied by an even longer delay as the slave wires cooled and returned the slave lever to its start point.

Concern with overheating prevented power increases that might have led to a quicker contraction response. On the other hand, the absence of temperature feedback may have led to heating well beyond the transition range, thus exacerbating the cooling problem.

COOLING THE SMA WIRES

To decrease the system's response time during extension of the SMA actuators, the actuators must be cooled more quickly. In an attempt to obtain a significant increase in the rate of cooling, we experimentally compared the cooling rate of the SMA wire in both water and a water/glycol mixture to its cooling rate in air. Appendix A contains details of this experiment, including plots of the response of the wire in the three cooling media.

The SMA cooling time constant in air, based on the experiment, is 0.62 seconds. For water, the time constant was 0.04 seconds; and for the 50/50 water-glycerol mixture, the time constant was 0.06 seconds. Not surprisingly, liquid cooling of the SMA wires offers significant improvement in response time. This works to the designer's advantage if the robot operates in a liquid environment, as does one miniature undersea SMA design

[5]; however, in most applications the need for liquid cooling is a serious disadvantage. The need for bulky cooling apparatus counters the power-to-weight advantages of SMA.

Investigators universally acknowledge the cooling problem, and have suggested several solutions. Heat sinks have improved the response of straight SMA wires, but do not seem practical with SMA springs. Unfortunately, springs may be more promising for most applications requiring significant actuator travel. Escher and Hornbogen have even suggested coating SMA wires with an elastomer to increase their radiating surface area without a correspondingly large increase in thermal mass [16].

APPLICATIONS OF SMA FORCE-FEEDBACK ACTUATORS

SMA force-feedback systems should benefit from SMA's advantages in slave manipulator and master feedback actuation. The outstanding power-to-weight ratio of SMA makes it well suited to extend slave operations to a smaller scale. Furthermore, cooling problems diminish greatly as the volume of the SMA actuator (and thus the ratio of its thermal mass to radiating surface area) diminishes. At least one SMA micro-manipulator has already been tested [9]. SMA could find a niche in teleoperated mini- and micro-manipulators.

Advantages of using SMA for master feedback actuation include its light weight and small volume. Bulkiness and weight are major disadvantages of many current and proposed force-feedback hand masters, since the handmaster must be carried on the user's hand, and actuators are usually placed on the hand or forearm. Further, an SMA master feedback device paired with an SMA slave actuator could take advantage of similar control circuitry and response characteristics.

SMA actuators have already been applied in automated clean room operations to grip silicon wafers [5, 7]. Unlike DC motors or other actuators, SMA actuators do not produce particulates or other contaminants. The inherent cleanliness of these actuators has given them a distinct superiority in some applications. SMA devices might likewise meet teleoperator requirements in a clean environment. Any application will need to overcome or be insensitive to SMA's power consumption, heat dissipation, and limited motion challenges.

AREAS OF FUTURE INQUIRY

Currently evolving microprocessor-based control schemes will rely on PWM power control and a more accurate knowledge of the internal states of the SMA wires. Internal resistance feedback or temperature feedback will allow quick heating just past the transition range but no farther. This should yield maximum contraction performance without inhibiting the cooling required for relaxation.

A flexible testbed based on these principles will allow quantitative experimentation with various classical and modern feedback methods. Effort will be required to determine how to best select and use the state variables when both position and force must be controlled. Innovative solutions to cooling and other design problems (such as limited actuator travel) will extend the useful range of SMA actuators in force-feedback applications.

CONCLUSION

Shape memory alloy actuators may be applied to force reflection systems; however, they remain subject to disadvantages

revealed by previous research: heat dissipation requirements, limited actuator travel, and slow response time. Low efficiency and the difficulty in obtaining actuator motion over a large enough distance create the most serious obstacles. SMA cannot currently compete with actuators such as electric motors, but new design ideas may change this for niche applications with serious actuator mass restrictions and with a tolerance of lower bandwidth actuation. One promising idea is a capstan roller tagonist-antagonist (one flexion actuator, one extension actuator) design from Boeing, in which the capstan serves as a heat sink and a method of rolling the long wire to fit it in a compact space [17].

Data on SMA actuator step responses should be obtained to accurately compare SMA bandwidth to that of competing actuators, so that tradeoff decisions may be made. Further investigations of mechanical design issues, cooling, and control will determine the utility of SMA materials for fully-articulated force-reflecting hand exoskeletons. At the very least, such investigations will expand the knowledge base available to take advantage of future materials.

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APPENDIX A

A ONE-DEGREE-OF-FREEDOM MASTER-SLAVE DEVICE BASED ON A SHAPE MEMORY ALLOY ACTUATOR

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Abstract

A one-degree-of-freedom master-slave device was built using shape memory alloy (SMA) wires for actuation. A bang-bang control scheme was used for both the position control of the slave and the force control of the master. A proof-of-concept prototype was built to demonstrate stability and other aspects of the design concept.

Air cooling of the SMA wires proved inadequate, causing the slave to lag behind the master when the slave wires were being returned to extended length. An experiment to determine the cooling time constants for the SMA wire in air, water, and a 50/50 mixture of water and glycerol showed that liquid coolants cause a significant increase in the cooling rate.

It was necessary to limit the driving voltage of the SMA wires of both master and slave to prevent their over-heating. Unfortunately, limiting the voltage to an arbitrary value inhibited performance; the highest allowable voltage should be used to obtain fast reaction times. An experiment was performed

to examine the feasibility of an infrared phototransistor for temperature detection, so that higher voltages could be used without danger of overheating. The experiment did not show IR temperature detection to be practical.

Introduction

The shape memory effect (SME) exhibited by certain alloys has been known for a number of years. Unfortunately, a host of problems hindered most early applications of SME. The problems include cost, slow response, and difficult characterization of properties and behavior. A new wave of activity was initiated with the discovery of the shape memory effect in an alloy of titanium-nickel, by Buehler, et al. (1963) [1]. The new alloy was named "nitinol," an acronym of Nickel, Titanium and NOL, for U.S. Naval Ord~~i~~nance Laboratory. Although an improvement over other SMA's, nitinol also proved problematic, without many practical applications. In 1985, the Toki Corporation, Tokyo, Japan, announced an improved, but proprietary version of nitinol under the trade name "BioMetal"[2]. BioMetal has an improved grain structure which results in longer fatigue life and a 200 percent reduction in recovery force. The improvement in fatigue characteristics is significant not only in terms of life, but also in terms of the allowed percent contraction of the wire. BioMetal is available only in 150 micron wire which appears to be an approximately optimum diameter with regard to adequate force levels and cooling.

As is characteristic of SMA's, BioMetal is capable of delivering large forces with small actuator size. A solenoid, for example, capable of delivering a comparable force, would be quite large and heavy. The favorable force-to-weight ratio of BioMetal makes it a possible candidate for use as an actuator. The goal of the present work is to explore the feasibility of incorporating BioMetal in a bilateral, force-reflecting, master-slave device.

Development of a Proof-of-Concept Prototype

A brief review of the properties of BioMetal did not reveal any inherent limitations that would prevent its use as an actuator. With the small diameter of only 150 microns, and by only heating to the minimum temperature necessary to elicit the shape memory effect, it was thought that air cooling might allow sufficiently rapid relaxation of the BioMetal wire. If necessary, it would be possible to introduce liquid cooling. Inventiveness appeared to be the main requirement for the solution of most problems. Therefore, it was decided to proceed with the development of a proof-of-concept prototype. The prototype would be sufficiently flexible to allow for an evolutionary development.

First, it was necessary to develop a concept for accomplishing the master-slave function. The basic operation requires position control of the slave and force control of the

master. There was also the design and selection of hardware from the standpoint of both electrical and mechanical components. It was decided that a single degree of freedom prototype would be built to test various aspects of the concept. The need for a compact, knuckle-sized design did not seem warranted until the basic operational feasibility was established. Thus, the prototype was built without spatial constraints.

The basic mechanical configuration is shown in Figure 1. Both master and slave links consist of simple levers made of balsa wood. Photographs of the original device are shown in Figure 2. The displacement transducers labeled in Figure 1 consisted of an infrared transistor fixed in one end of a tube and an infrared LED that was free to move in the other end. The motion of the LED was caused by the displacement of the master or slave. As expected, the transducers were highly nonlinear. However, the nonlinearities had enough similarity to provide a reasonable correspondence between the motions of the master and slave.

The circuit for the position control of the slave is shown in Figure 3. The bridge is balanced with both master and slave in the same angular position. Any subsequent motion of the master causes the bridge to be unbalanced causing a correction in the slave position by either turning on or turning off the slave SMA wires. The rubber band on the slave in Figure 1 provides a force of roughly 50 grams, which is sufficient to stretch the SMA wires when cooled. Due to the large initial stretch of the rubber band, the force remains fairly constant over the range of

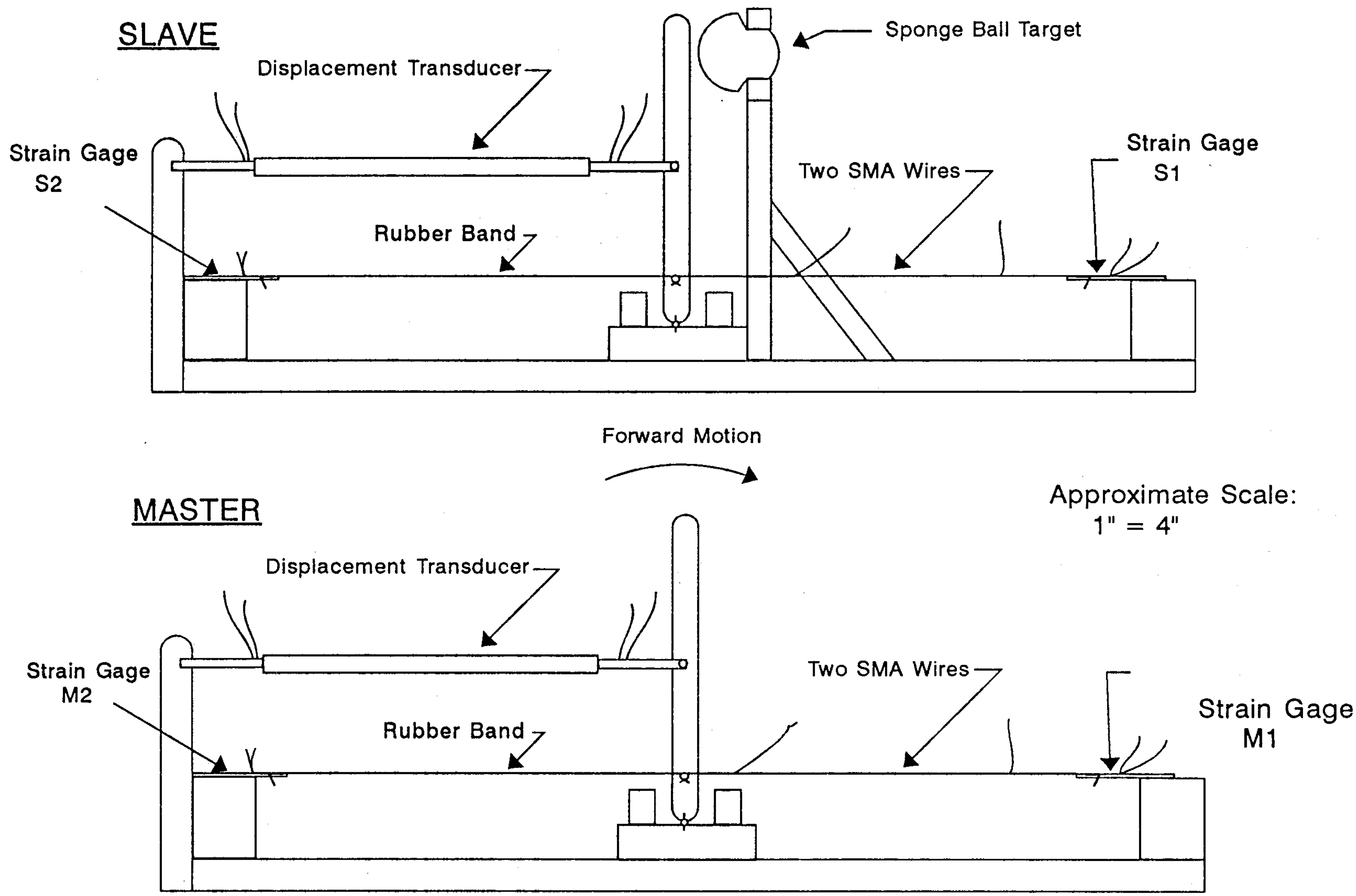

Fig.1. Schematic of Basic Mechanical Configuration for Master-Slave Device

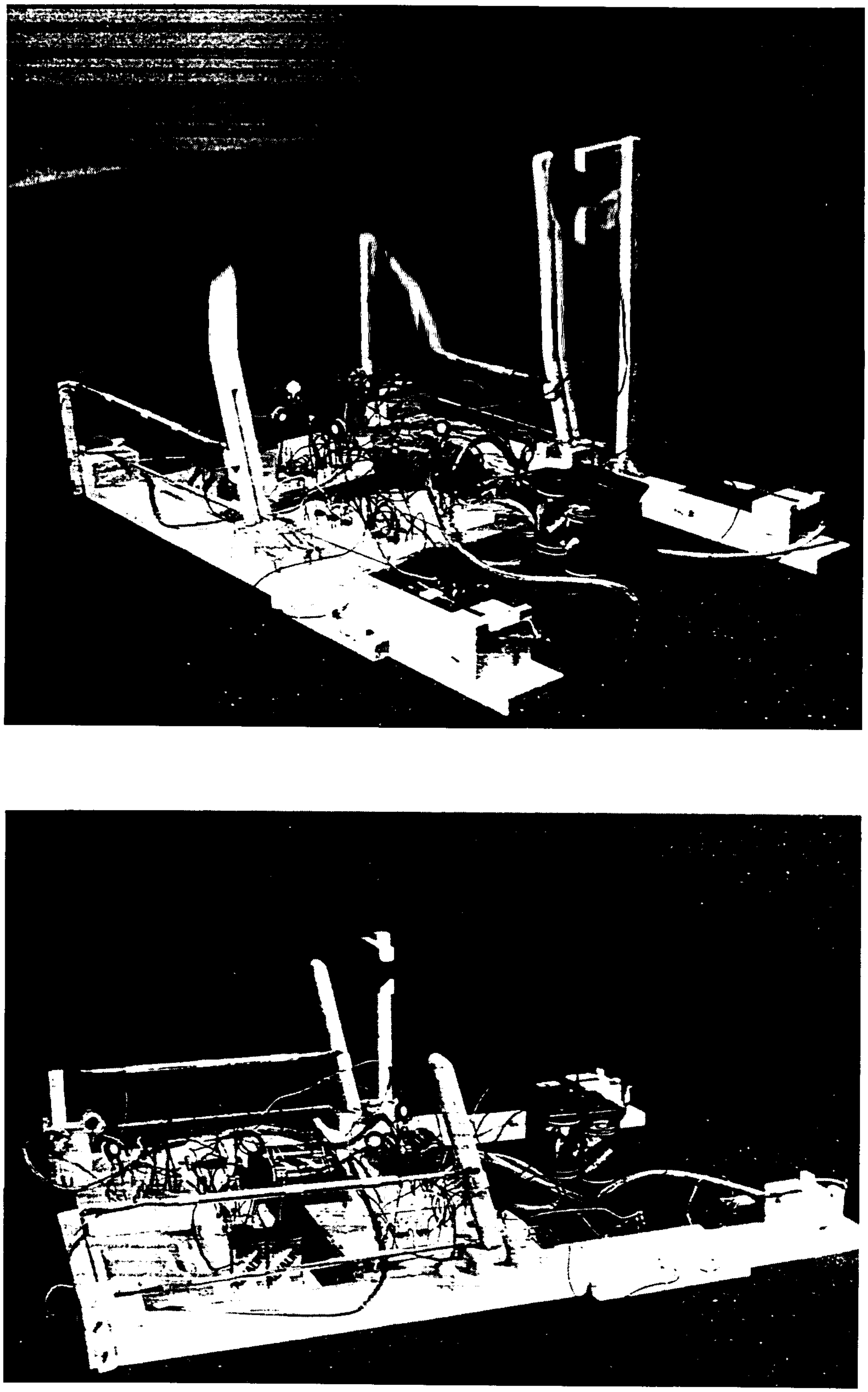

Fig. 2. Photographs of Master-Slave Prototype

POSITION CONTROL

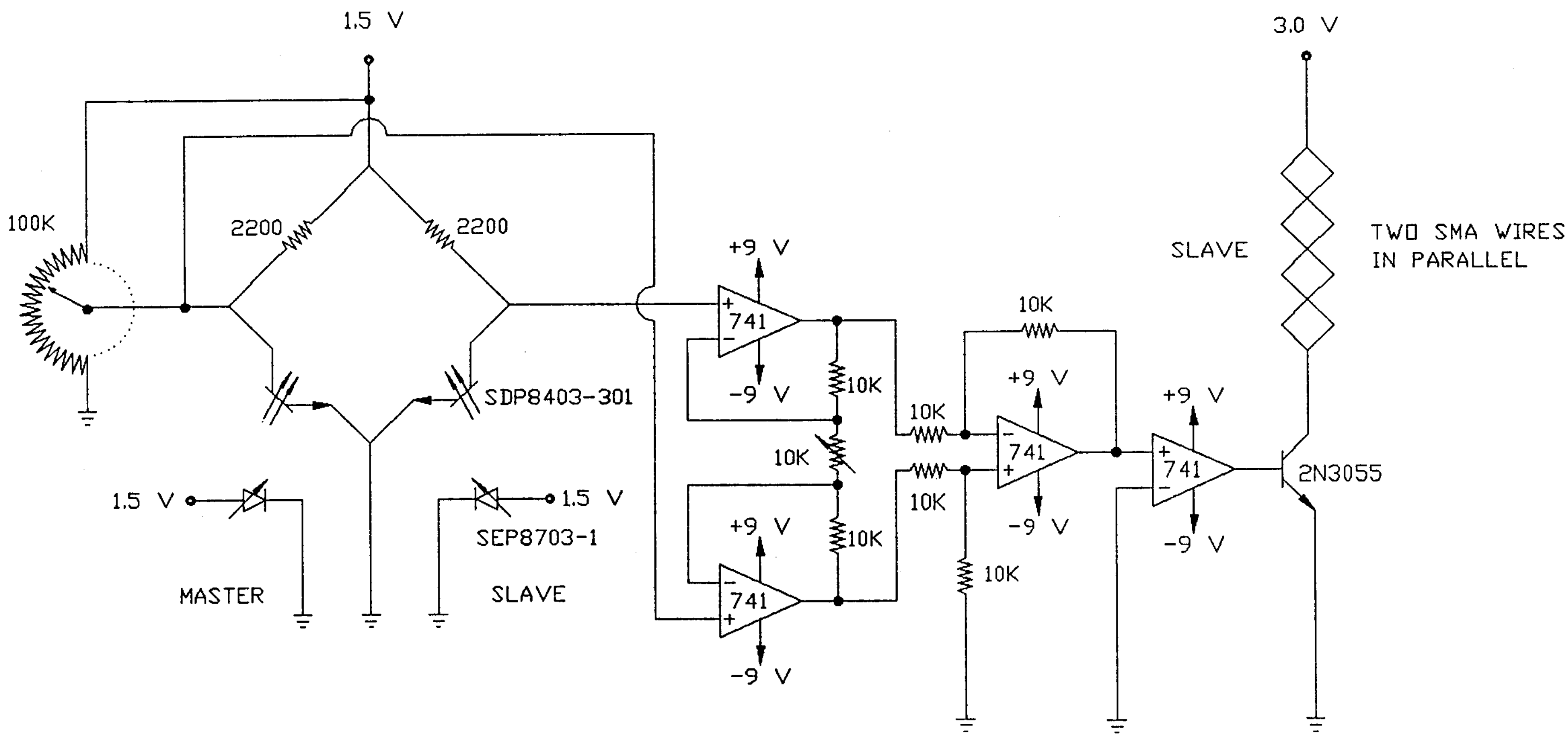

FIG. 3. CIRCUIT FOR SLAVE POSITION CONTROL

motion of the slave. The power transistor which drives the SMA wires is theoretically on or off due to the switching of the op amp comparator. It was demonstrated that the on/off or bang-bang control provided stable response. Equilibrium positions were achieved with no detectable limit cycling.

The circuit for the force control of the master is shown in Figure 4. The four strain gages in Figure 1 constitute the four legs of the bridge in Figure 4. Each gage has the same label in both figures. The procedure to balance the bridge is as follows: The SMA wires on both master and slave are adjusted so that neither of the levers is in contact with the stops. Also, neither lever is subject to any external force, i.e., the slave is not touching the target. The combined force in the two SMA wires is exactly equal to the force in the rubber band in both the slave and master. The 100K ohm potentiometer is then used to balance the bridge.

The operation of the force reflection will now be explained. When an attempt is made to move the master lever, there is an instantaneous change in tension in the SMA wires. For example, if the motion of the master is to the right in Figure 1, the tension in the SMA wires will be reduced. There will only be a very slight increase in the tension in the rubber band due to the much lower spring constant. Since the change in resistance of the strain gages is proportional to the tension, the bridge becomes unbalanced causing the SMA wires of the master to become activated. The net effect is that only a very slight force is required to move the master. When the slave contacts the target

FORCE REFLECTION

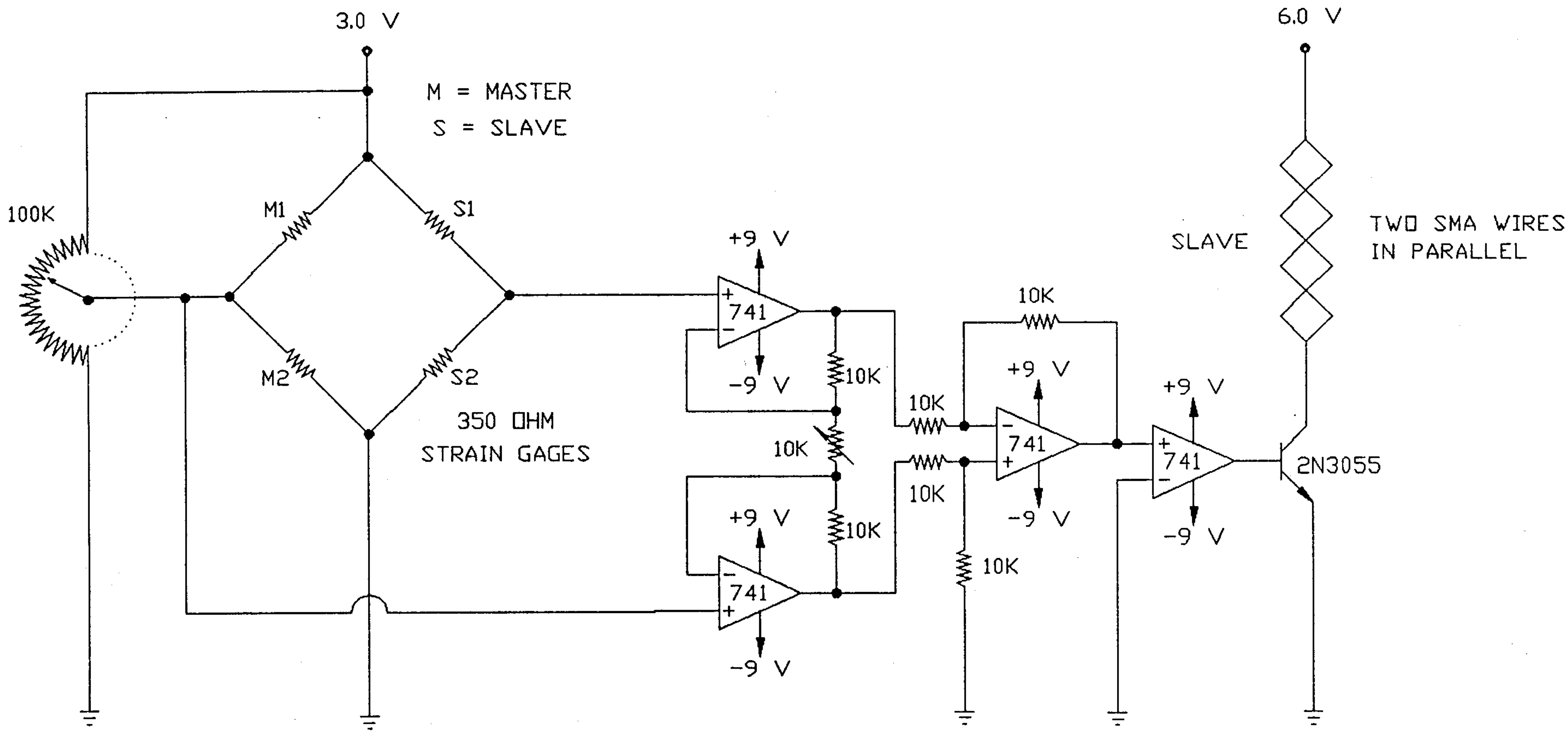

FIG. 4. FORCE CONTROL CIRCUIT

sponge ball, the tension in the slave SMA wires increases, causing the bridge to again be unbalanced. The unbalance increases the tendency for the SMA wires of the master to be off unless the tension in the rubber band of the master is greater than the tension in the SMA wires. The difference in tension is maintained by the force of the human operator. The force felt by the human operator is the same force that the slave exerts on the sponge ball. It is assumed that the force applied by the human operator is at roughly the same location on the master as the sponge ball contact on the slave.

Cooling the SMA wires

A rapid return motion of the master caused the slave to follow with a discernable lag. The lag occurred because the natural convection of the slave wires in air provided an inadequate rate of heat transfer. It was anticipated that this problem might exist but would have been difficult to predict due to inadequate knowledge of the response times for incomplete transitions of the SMA. It was estimated that the cooling rate needed to be at least ten times faster. It would be difficult to obtain the necessary increase in the rate of cooling without introducing a liquid coolant. Since water is one of the best coolants, and since BioMetal is highly noncorrosive, it was decided to perform some tests to compare the rate of cooling in water to the rate of cooling in air.

Figure 5 shows the test set up. A four inch length of SMA

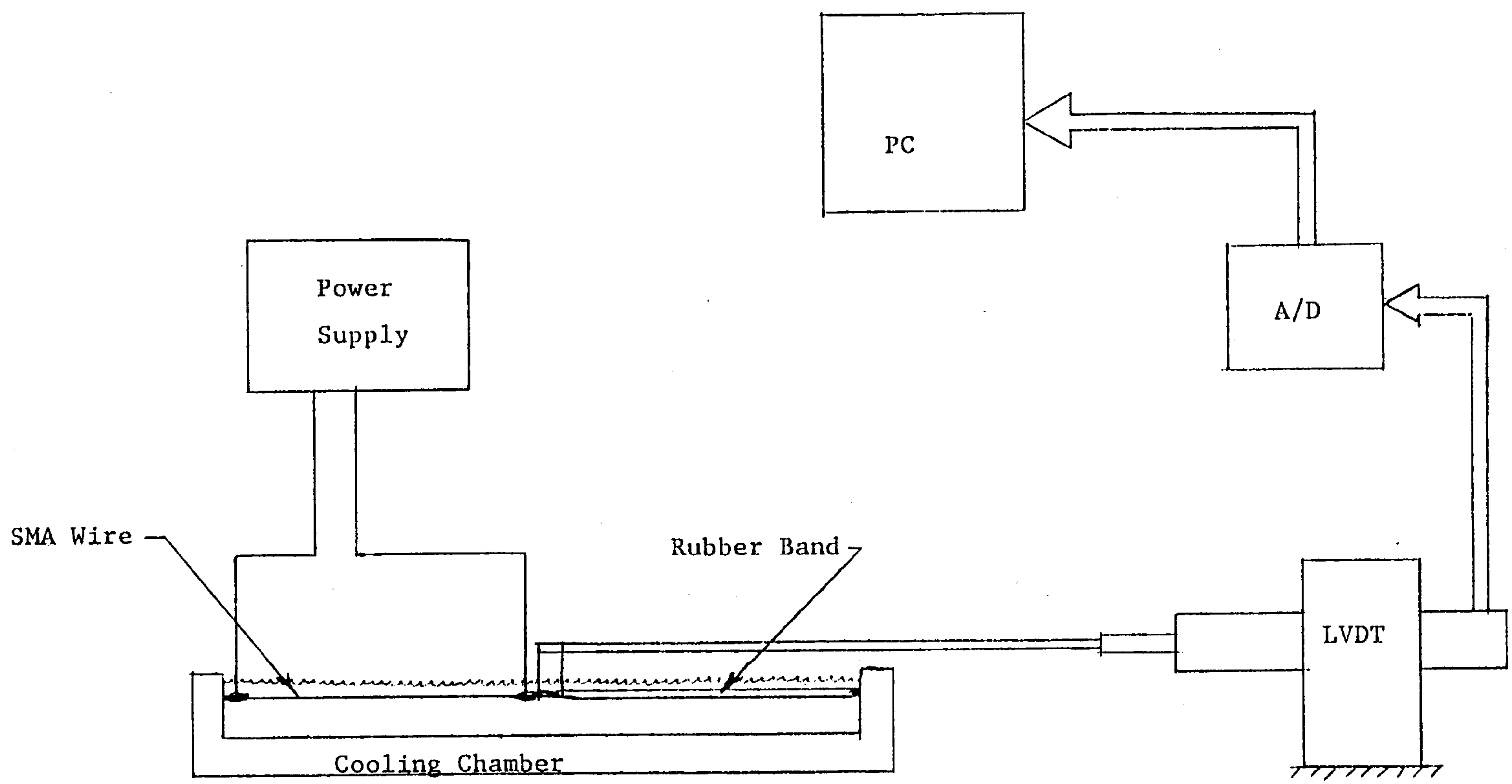

Fig. 5. Test Setup to Obtain SMA Response Due to Cooling

wire was held in tension by a rubber band. A voltage was applied to the SMA wire producing a .1 inch contraction. Just before opening the switch, a data acquisition program was started on the PC. The return motion to uncontracted length by the SMA wire was detected by the LVDT, and fed to the PC through an A/D converter. Since the motion is essentially a first-order response, the time constants serve as the basis for comparison.

Data were obtained for three cases of cooling. The SMA wire was cooled in air, in water, and in a 50/50 mixture of glycerol and water. The results are shown in parts a, b and c of Figure 6. The numbers on the vertical axes of the graphs reflect the eight-bit resolution of the A/D converter. The time constant in air based on these data is .62 seconds. For water, the time constant was .04, and for the 50/50 water-glycerol mixture, the time constant was .06 seconds.

<u>Temperature Sensing by Infrared Detection</u>

The contraction time for the SMA wire can be optimized by using high voltages to heat the wires. However, to avoid damage to the wire, the voltage must be immediately reduced to zero if the temperature of the wire exceeds a safe level. The sensing technique used must be capable of fast response and also must not interfere with the heating and cooling of the SMA wire. To meet these requirements, the sensing of temperature by infrared

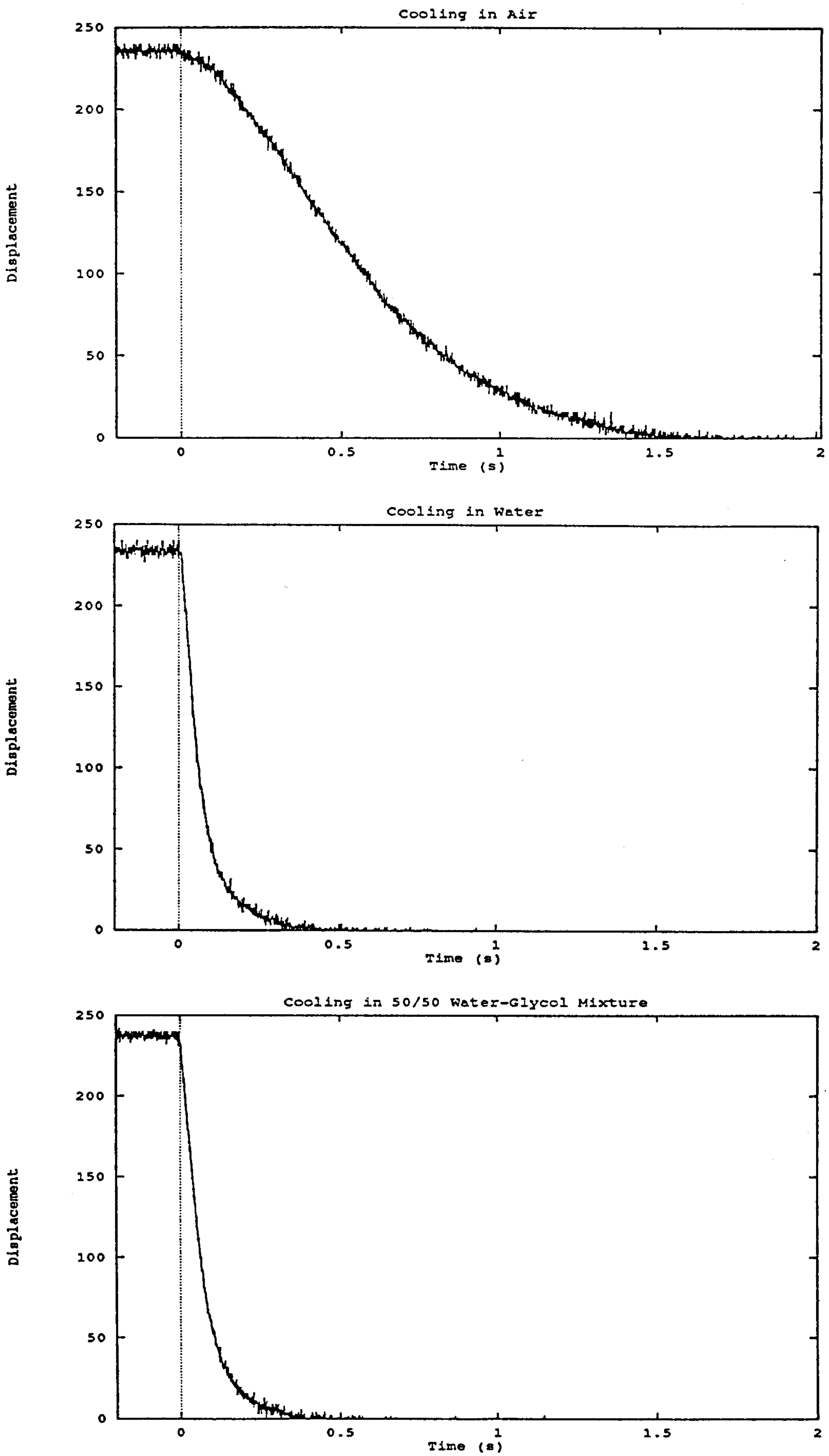

Fig. 6. Data from Cooling Tests: (a) Air (b) Water (c) 50/50 Water and Glycerol

detection was investigated.

An experiment was performed using an infrared phototransistor from Radio Shack, part number SDP8403-301 [3]. The device costs less than one dollar, and unlike many devices for infrared detection, has the compact size needed for use in a compact actuator design. Unfortunately, the spectral response of the phototransistor was unknown, as well as threshold detection levels. Since only a small effort was required to build the circuity, it was decided to test the responsiveness of the phototransistor for detecting infrared radiation from the SMA wire.

Figure 7 shows the test arrangement. The infrared transistor served as a variable resistor in a bridge circuit as indicated in Figure 7. The output of the bridge was fed into a high-gain amplifier. The gain was set as high as possible without picking up background noise by the unshielded leads. The gain was estimated to be between 10,000 and 100,000. The SMA wire was placed as close as possible to the P-N junction of the infrared transistor by drilling a small hole in the plastic lens of the transistor and running the wire through. The transistor and the SMA wire were mounted inside a box made of 1/2 inch thick balsa wood. To shield all ambient radiation, the box was wrapped with several layers of tin foil. Before applying the tin foil, the transistor inside the closed box was found to be extremely sensitive to ambient lighting. For example, with the voltmeter set at .25 volts full-scale, wide swings in the voltmeter reading could be produced by waving a hand over the box. With the box

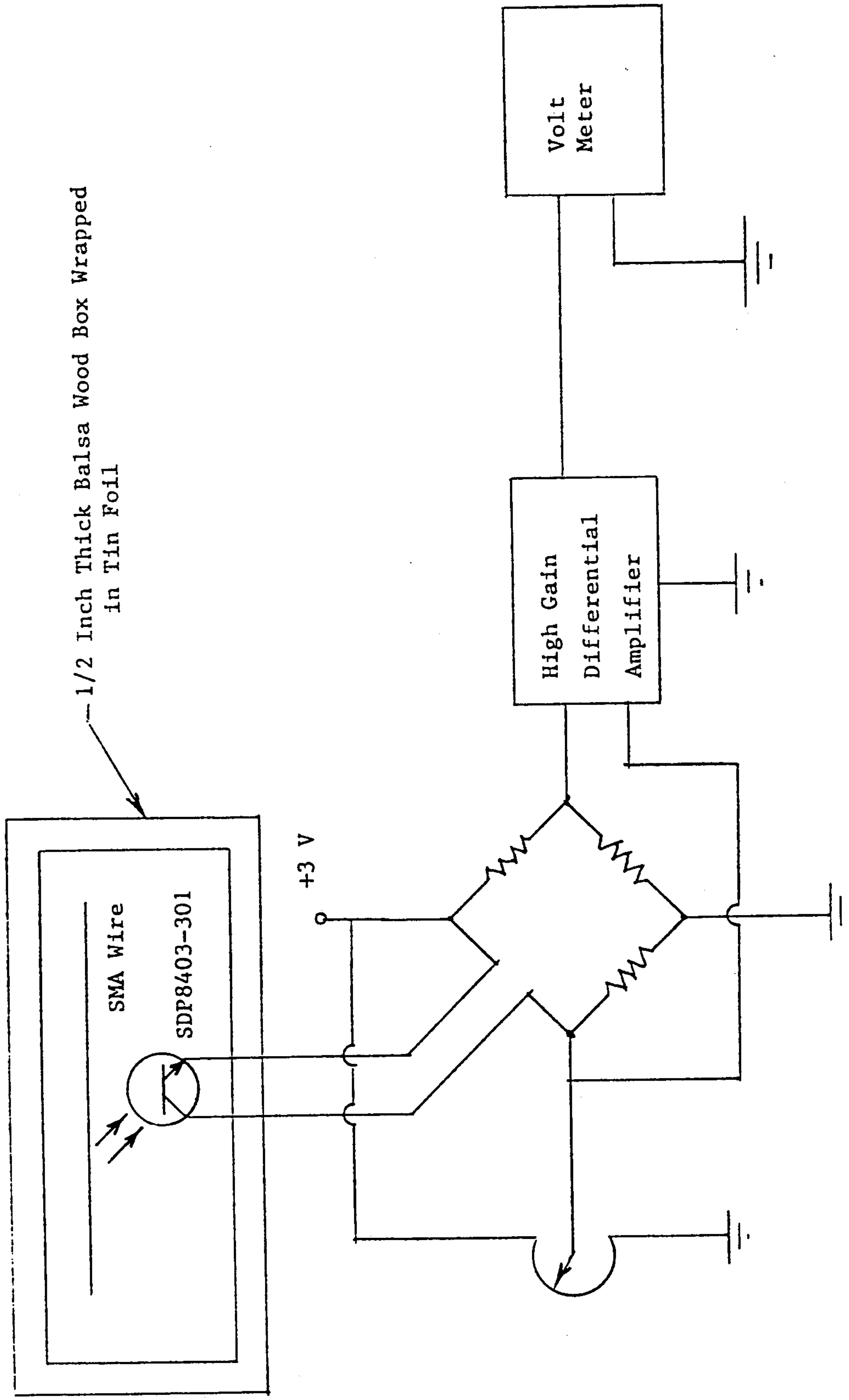

Fig. 7. Test Setup for Infrared Thermal Detection

closed and wrapped in tin foil, the SMA wire was heated up to and beyond the damaging temperature level. Unfortunately, no detection was evidenced by a movement of the volt meter.

The lack of thermal detection by the infrared transistor may have been due to radiation levels below a threshold, or due to spectral mismatch, or both. The electromagnetic radiation frequency for peak response for the transistor was unknown, as well as the distribution of the frequency spectrum. However, the transistor is commonly used in combination with the Radio Shack infrared emitting diode, SEP8703-1, which has a peak output at 915 nm. Planck's equation for the spectral radiant emittance W_λ, expressed in watts/($cm^2 \mu m$) at a wavelength λ [μm] from a blackbody at absolute temperature T (Kelvin) is given as [4],

$$W_\lambda = \frac{2\pi hc^2}{\lambda^5}\left(\frac{1}{\exp\left(\frac{ch}{\lambda kt}\right)-1}\right) \tag{1}$$

Where,

h = Planck's Constant in watts sec^2

c = Velocity of light in m/sec

k = Boltzmann's constant, in watts sec/K

The peak emission wavelength λ_M, is obtained from Wien's displacement law,

$$\lambda_M T = 2898\ \mu m\ K \tag{2}$$

which can be derived from Planck's equation.

The maximum safe temperature for the SMA wire is around 300 C, or 573 K. Substituting this value into Eq. 2 gives a peak emission wavelength of 5 microns. A lead selenide infrared detector[5] from Infrared Industries, Inc., series 4080, having a spectral response from 1 to 4.7 microns, has been acquired but not yet tested. Built-in cooling systems required for longer wavelength infrared detectors make them bulky and expensive.

Conclusions

The conceptual feasibility of a master-slave device, based on a SMA actuator, has been demonstrated. However, the prototype design was simplified by disregarding spatial constraints. One performance weakness of the device was a noticeable lag in the return motion of the slave due to slow cooling of the SMA wire in air. The cooling rate experiments described above show that water cooling provides roughly a 15-fold increase in the cooling rate. The time constant for the return motion in air was .62 seconds, whereas the time constant in pure water was .04 seconds.

The low energy efficiency of BioMetal poses a challenge to the design of a compact actuator capable of delivering useful work. It is an unavoidable requirement to place as much of the SMA as possible into the smallest volume possible. SMA wire diameters must be small to avoid slow response times, even with water cooling. An actuator design must also "work around" the 5

to 6 percent contraction limitation of the SMA wire to provide a useful range of displacement with adequate force levels. In addition to the cooling requirement for dynamic response, low energy efficiency requires that 98 to 99 percent of the energy input be carried away as heat. Therefore, each actuator must have a tube to deliver cooling water and another tube to carry away the water when heated. In addition, peripheral heat exchanger equipment is needed to discard the heat. Although feasible, it seems that an SMA actuator would have difficulty competing with some other means of actuation, such as hydraulics.

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